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Letter

Lifetime of a new high-spin isomer in ^{150}Dy

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Abstract. A new high-spin isomer in ^{150}Dy has been observed at an excitation energy of 10.3 MeV by combining the inverse-kinematic reaction induced by a pulsed beam of ^{132}Xe and the γ-ray recoil-shadow technique. The half-life of this isomeric state has been determined to be $T_{1/2} = 1.6 \pm 0.6$ ns using the conventional centroid-shift method with the ^{141}Pr(^{16}O, p6n)^{150}Dy reaction at 165 MeV. The mechanism producing high-spin isomers in $N = 83, 84$ isotones is qualitatively discussed in terms of the difference of the neutron particle-hole configuration between the high-spin isomer and the lower-lying state.

PACS. 21.10.Tg Lifetimes – 23.20.Lv γ transitions and level energies – 27.70.+q $150 \leq A \leq 189$

The region of $A \approx 150$ nuclei near the neutron closed-shell $N = 82$ has been well known as a vast treasure house of nuclear isomers [1]. This isomerism can be chiefly ascribed to irregularities of the level spacings in the yrast region composed of states of single-particle nature [2]. In most cases, these "yrast traps" seem to have the aligned-particle configurations which drive the nuclei to oblate deformed shapes [3]. A particularly large equilibrium deformation is expected for the isomeric state at very high spin arising from the breakdown of the $N = 82$ core, as confirmed for ^{147}Gd by the measurement of the electric quadrupole moment [4]. The analogous high-spin isomers have been also observed for $N = 83$ isotones with $60 \leq Z \leq 66$ at almost constant excitation energies ($E_{\mathrm{ex}} = 8$–9 MeV) [5–11]. On the other hand, the corresponding systematics has not yet been confirmed for $N = 84$ isotones, among which the high-spin isomers have been reported in ^{148}Gd ($I = 35$, $T_{1/2} \sim 2$ ns [12]) and ^{149}Tb ($I^{\pi} = 61/2^{+}$, $T_{1/2} = 4.0$ ns [13]). The nucleus ^{150}Dy, which has two protons and two neutrons outside the ^{146}Gd core, has proven to be interesting in the point that both the $Z = 64$ and $N = 82$ core excitations occur at the same excitation energy in separate parallel cascades [14]. Furthermore, the γ-ray spectroscopic data previously obtained for the high-spin states of this nucleus suggested that there might be an isomeric state with a half-life of a few nanoseconds above the 8610 keV level [15]. These facts highly motivated us to search for a new high-spin isomer in ^{150}Dy.

We have performed two types of experiments separately to probe the high-spin states in ^{150}Dy. In the first experiment, the nucleus ^{150}Dy was produced via the ^{141}Pr(^{16}O, p6n) reaction with an energy of 165 MeV provided by the SF-cyclotron at the Center for Nuclear Study (CNS), University of Tokyo. A refined praseodymium foil of 7.2 mg/cm^2 thickness was enough to retain the reaction products within the target. Five HPGe detectors with BGO anti-Compton shields were arranged around the target. The experimental data were acquired when at least two Compton-suppressed Ge detectors were fired concurrently. A total of 1.7×10^8 events were recorded during this experiment. The second experiment has been carried out with a 6 mg/cm^2 natural magnesium target

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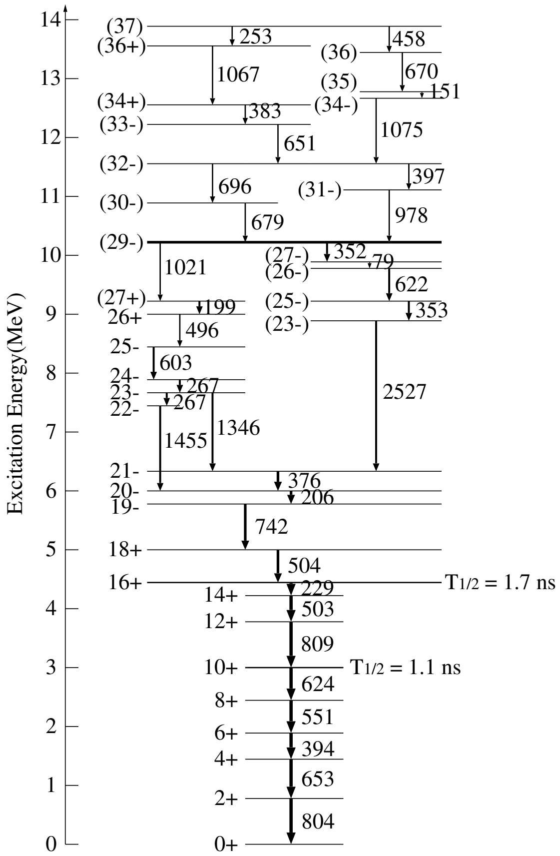

Fig. 1. Partial level scheme of ^{150}Dy confirmed in the present work. The values of spin-parity, which are enclosed in parentheses for tentative assignments, have been given in ref. [14].

irradiated by a projectile of ^{132}Xe accelerated up to an energy of 7.0 MeV/nucleon by the RIKEN Ring Cyclotron. The beam burst was pulsed with an interval of 1 μs and a width of ≤ 1 ns. The reaction products which recoiled out the target with a mean velocity of $0.07c$ were gathered on a lead foil placed 7 cm downstream from the target. It took about 3 ns to pass through this area. The production target was effectively shielded by lead blocks so that the prompt γ-rays were not observed by Ge detectors. The combination of the pulsed beam and the recoil-shadow method with the inverse-kinematic reaction allowed us to measure only γ-rays emitted via isomeric states whose half-lives range from a few nanoseconds to sub-microseconds. Five HPGe detectors were used to measure the delayed γ-rays from the stopper position. The details of this experimental setup are described in ref. [16].

Before the present work the level scheme of ^{150}Dy was established by Deleplanque *et al.* for the yrast levels up to spin of about 40 $\hbar$ and $E_{\mathrm{ex}} \leq 16$ MeV [14]. We have carefully examined the coincidence relationships among main transitions by analyzing the E_γ-E_γ matrix within a prompt-time window ($\Delta t = \pm 25$ ns) obtained in our first experiment. Figure 1 shows a partial decay scheme confirmed in this work.

A convincing evidence of a new isomer could be extracted from the experimental data acquired with the recoil-shadow method. Comparing the $\gamma\gamma$-gated spectra for ^{150}Dy measured in the above two experiments, the γ-rays de-exciting the states higher than the $E_{\mathrm{ex}} = 10.3$ MeV level could be clearly observed in the first experiment (fig. 2(A)), while only the transitions below that state were detected with the recoil-shadowing setup (fig. 2(B)). This indicates that the 10.3 MeV state has a half-life of more than a few nanoseconds. Furthermore, it is found in fig. 2(A) that the 376 keV transition, where both the cascades de-exciting the 10.3 MeV state flow into (see fig. 1), is roughly comparable in intensity to the "doublet" 353 keV peak. This is probably due to the strong side-feedings which directly populate the yrast states at 6.5 MeV $\leq E_{\mathrm{ex}} \leq$ 10 MeV from the entry region for the evaporation residue of ^{150}Dy* produced by the ^{141}Pr(^{16}O, p6n) reaction. In fig. 2(B), on the other hand, the 353 keV peak is more prominent than the 376 keV one in spite of the same gating conditions as in fig. 2(A). The angular-momentum distributions in the entry regions of ^{150}Dy* formed in the two systems are expected to be nearly equal by the statistical-model code CASCADE [17]. Therefore, there might be no isomeric states which trap some part of γ-ray flow with lifetimes detectable with our recoil-shadowing setup besides the $E_{\mathrm{ex}} = 10.3$ MeV state at spin above 20 $\hbar$ in ^{150}Dy.

The half-life of the isomeric state at $E_{\mathrm{ex}} = 10.3$ MeV has been evaluated by means of the conventional centroid-shift method [18]. In this analysis we created background-subtracted time-differential (TDF) spectra between two specific transitions within a coincidence window. The shift of the centroid position could be observed as the deviation from the prompt-TDF spectrum, which was gated by γ-rays with energies near to those of interest in the delayed-TDF spectrum. The resultant TDF spectra are exhibited in fig. 3. In order to derive the corresponding half-life from the observed centroid shift, we have calibrated the TDF spectra using the well-known value of $T_{1/2} = 1.1 \pm 0.3$ ns for the $I^\pi = 10^+$ isomer in ^{150}Dy [19] (see fig. 3(A)). As shown in fig. 3(B), we have finally determined the half-life of the new high-spin isomer in ^{150}Dy to be $T_{1/2} = 1.6 \pm 0.6$ ns.

A good deal of interesting information about the structure of the new isomer can be obtained from the transitions de-exciting the isomeric state. As shown in fig. 1, the decay of the isomeric state at 10.3 MeV mainly proceeds through two separate parallel cascades down to the 20^- level. For the 352 keV and 1021 keV transitions placed at the top of each cascade, we have deduced transition probabilities from the measured half-life and their intensities. The resultant values are listed in the third column of table 1. Unfortunately, the multipolarities of these transitions could not be experimentally determined. On the basis of the systematics for the decay of the high-spin isomers in the $A \approx 150$ region, it seems that the multipolarities of the γ-rays de-exciting the new isomer are of dipole or quadrupole character. The enhancement factors F of these transitions have been calculated for possible multipolarities in W.u. The estimated values are also summarized in table 1. We could entirely exclude the

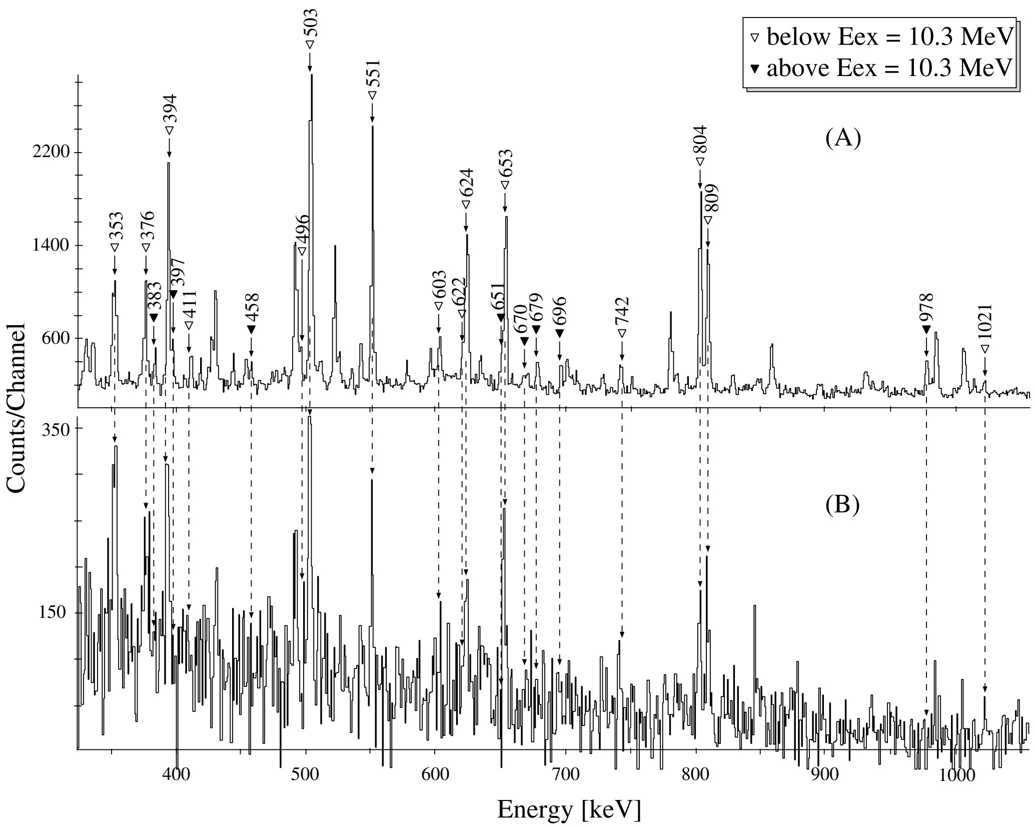

Fig. 2. $\gamma\gamma$-coincidence spectra for ^{150}Dy measured at (A) the target position in the first experiment, (B) the stopper position with the recoil-shadowing geometry in the second experiment. Both of the figures are created by summing up spectra gated by known transitions; 742 keV ($19^- \to 18^+$), 206 keV ($20^- \to 19^-$), 1455 keV ($22^- \to 20^-$), 1346 keV ($23^- \to 21^-$). The energies are noted for the γ-rays below (open triangle) and above (solid triangle) the $E_{\rm ex} = 10.3$ MeV state in ^{150}Dy.

possibility of the $M2$-character for the 352 keV transition because its strength exceeded a recommended upper limit given in ref. [20]. The spin-parity assignments have been firmly done up to the $I^\pi = 26^+$ level at 9 MeV in one cascade [14]. Since the spin increases monotonously with the excitation energy along the strong decay pathway in this region, the new high-spin isomeric state is expected to have spin 28 or 29 $\hbar$.

In the previous work for the high-spin states in ^{150}Dy [14], the γ-cascade constructed from the 1455-267-267-603-496-199-1021 keV transitions have been interpreted as a proton particle-hole branch, while the 2527-353-622-79-352 keV transitions as a neutron one. It is well known that nearly spherical shapes should persist as long as the $N = 82$ core keeps intact, even though the $Z = 64$ core is broken, whereas relatively large oblate deformations are induced by neutron particle-hole excitations across the $N = 82$ shell-gap [21]. Namely, the coexistence of spherical and oblate states occurs in the yrast region above the spin 20 $\hbar$ level in ^{150}Dy. As systematically confirmed for all neighboring Dy isotopes [15], the proton particle-hole states form the yrast line in ^{150}Dy as well. However, as shown in fig. 4, the γ-ray flow stemming out of the isomeric state predominantly favors the *non-yrast* neutron particle-hole stream. Similar phenomena have also been observed in ^{147,148}Gd [12].

The new high-spin isomer in ^{150}Dy is expected to have a one-proton and a one-neutron particle-hole configuration on the basis of the fact that both the proton and neutron particle-hole sequences start from this state. According to a deformed independent particle model (DIPM) calculation [21], the $I^\pi = 28^-$ or 29^- state can be firstly produced by such configurations in the yrast region. On the other hand, the configuration of the $49/2^+$ long-lived isomer in ^{147}Gd ($T_{1/2} = 550$ ns) has been unambiguously determined to be $\pi(h^2_{11/2}(d^{-2}_{5/2})_0)\otimes\nu(f_{7/2}h_{9/2}i_{13/2}(d^{-2}_{3/2})_0)$ by the measurement of the g-factor [22]. The DIPM calculation predicts that the corresponding state in ^{150}Dy to this largely oblate deformed isomer is most likely the $I^\pi = (27^-)$ state, for which the stretch-aligned $\pi(h^2_{11/2})\otimes\nu(f^2_{7/2}h_{9/2}i_{13/2}(d^{-2}_{3/2})_0)$ configuration is proposed, located at 352 keV below the 10.3 MeV isomeric state in the neutron particle-hole branch of ^{150}Dy. However, this state has not been identified as an isomer as well as the $I^\pi = 27^-$ state in ^{148}Gd [12]. The reason why these counterparts cannot have long lifetimes may be that these states mainly decay into the lower-lying states which belong to the respective neutron particle-hole sequences. In contrast, the transition from an "oblate" neutron particle-hole state to a "spherical" proton one is strongly inhibited. The long lifetime of the two-neutron particle-hole isomer in ^{147}Gd

Table 1. Relative intensities I_γ and transition probabilities $T(\sigma\lambda)$ of the γ-rays depopulating the $T_{1/2} = 1.6 \pm 0.6$ ns isomer in ^{150}Dy. The enhancement factors F were evaluated for possible multipolarities in units of the Weisskopf estimate.

E_γ (keV)	I_γ (%)	$T(\sigma\lambda)$ (/s)	$F = T(\sigma\lambda)/T^W(\sigma\lambda)$			
			$E1$	$E2$	$M1$	$M2$
352	76	2.7×10^8	2.1×10^{-6}	0.87	2.0×10^{-4}	80
1021	24	8.4×10^7	2.7×10^{-8}	1.3×10^{-3}	2.5×10^{-6}	1.2×10^{-1}

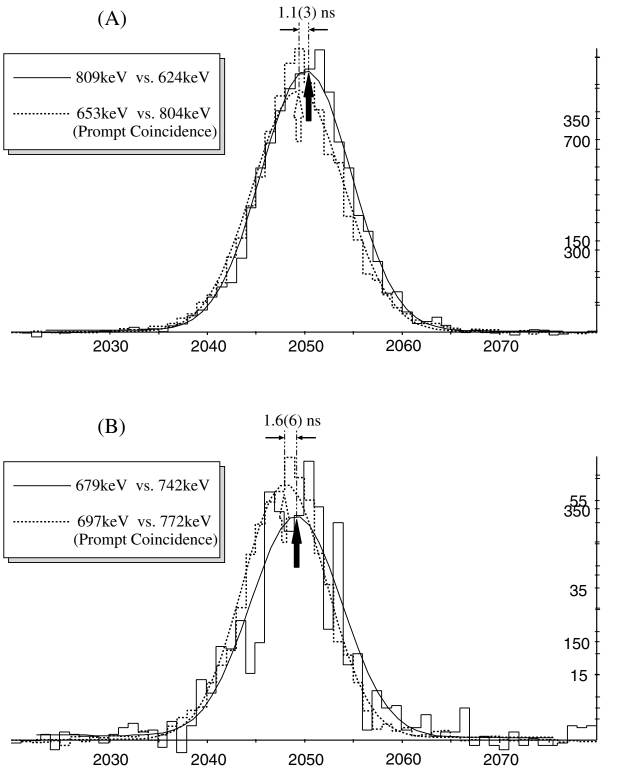

Fig. 3. Time-differential spectra measured in the present work. Solid lines represent the delayed coincidences, and dotted lines the prompt ones. The upward arrows indicate the positions of the centroid given by the peak fitting program. After calibrating a shift of the centroid position for the known half-life $T_{1/2} = 1.1 \pm 0.3$ ns of the low-spin isomer in ^{150}Dy [19] in (A), a half-life of the $E_{\rm ex} = 10.3$ MeV state has been determined to be $T_{1/2} = 1.6 \pm 0.6$ ns in (B).

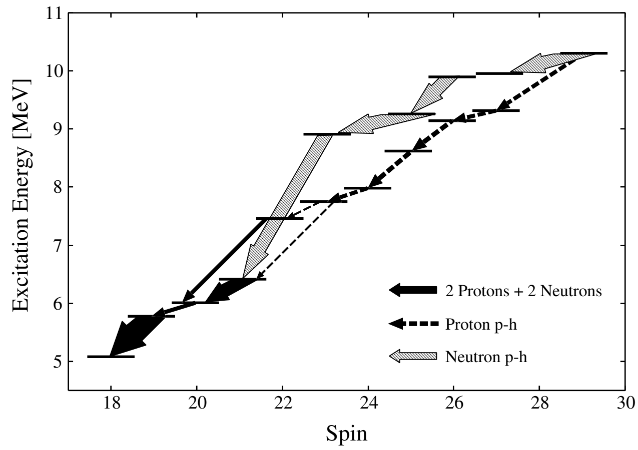

Fig. 4. Visualized two-dimensional γ-ray intensity flow stemming from the $E_{\rm ex} = 10.3$ MeV isomeric state down to the spin 18 $\hbar$ level in ^{150}Dy. The γ-rays going through the valence-nucleon, *i.e.* the two protons plus two neutrons, the proton particle-hole and the neutron particle-hole states are expressed by solid, dashed and hatched arrows, respectively. The width of the arrows represent the γ intensity.

can be attributed to such a great difference in the configuration with the lower-lying $47/2^+$ state, where one valence neutron is coupled to the three-proton particle-hole configuration. In the case of the decay from the 10.3 MeV isomer into the proton particle-hole branch in ^{150}Dy, the difference of the configurations does not seem to be large compared with the case in ^{147}Gd. In consequence, the 1021 keV transition in ^{150}Dy cannot be so strongly hindered as the $49/2^+ \to 47/2^+$ transition in ^{147}Gd, resulting in the short lifetime of the new high-spin isomer.

In summary, we have obtained the complementary data for the high-spin states in ^{150}Dy and have been able to assign a new isomer at the $E_{\rm ex} = 10.3$ MeV level. The analysis of the $\gamma\gamma$-time spectra yields a reliable half-life of 1.6±0.6 ns for this state. As a result of a comparison of the decay patterns out of the high-spin isomeric states, it has turned out qualitatively that the short lifetime of the new high-spin isomer is probably due to a smaller difference in the neutron particle-hole configuration between the high-spin isomeric state and the lower-lying one in ^{150}Dy than in ^{147}Gd. Unfortunately, we cannot pursue this argument further due to the lack of information about spin and parity assignments. Measurements of angular correlations and conversion electrons will be helpful in complementing our interpretation. In addition, detailed information about the configuration of the new high-spin isomer in ^{150}Dy will be provided by studying the nuclear g-factor.

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